Predictability Limitations of Long-Range Sound Propagation

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LONG-TERM GOAL

Our long-term scientific goal is to understand the basic physics of low-frequency long-range sound propagation in the ocean, and the effects of environmental variability on signal stability and coherence. We seek to understand the fundamental limits to signal processing imposed by ocean variability to enable advanced signal processing techniques, including matched field processing and other adaptive array processing methods.

OBJECTIVES

The principal objective of our ongoing effort is to develop a theory of acoustic fluctuations in long-range propagation that correctly accounts for measurements. This objective is motivated by the failure (as reported by Colosi *et al.*, 1999) of traditional approaches (see, e.g., Flatté *et al*., 1979) to the study of wave propagation in random media (WPRM) to predict measured time spreads and intensity statistics in recent long-range underwater acoustic experiments. Work to date strongly suggests that acoustic fluctuations are, to a surprisingly large degree, controlled by a property (the ray-based stability parameter α or the asymptotically equivalent mode-based waveguide invariant β) of the background sound speed profile, rather than details of the sound speed perturbation. As a result, much of the recent theoretical work has been motivated by a desire to understand which wavefield properties are controlled by α or β. Over the past two years a significant part of this effort has been devoted to the analysis of measurements made during the LOAPEX experiment.

APPROACH

The group in Miami (M Brown, F J Beron-Vera, I Udovydchenkov and I Rypina; note that IU and IR are now at WHOI) has employed a combination of ray- and mode-based theory, combined with PE simulations, to study and quantify acoustic fluctuations. Much, but not all, of the mode-based theory is based on an asymptotic analysis, as this provides a direct link to the ray-based analysis. Similarly, much, but not all, of the ray-based analysis makes use of action-angle variables, as this provides a direct link to the mode-based analysis. Another crucial connection between the ray- and mode-based analyses derives from the asymptotic equivalence of the ray stability parameter α and the modal

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14. ABSTRACT
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waveguide invariant β. Throughout the past year we have continued to extend relevant theoretical developments, but we have prioritized work involving the application of theoretical results to the analysis of measurements made as part of the recent LOAPEX propagation experiment. Specific topics/questions, which have been investigated by the PI during the past two years, are listed in the following section.

WORK COMPLETED

The work listed below is in various stages of completion. The work listed in items 1 and 2 has been published and, in this sense, is complete. The work described in item 3 represents a new – and important, we believe – theoretical direction. This is a fairly recent, and ongoing, initiative that is being pursued with I. Rypina and I. Udovydchenkov at WHOI. The ongoing work described in item 5 is being done in close collaboration with I. Udovydchenkov at WHOI.

1. Modal group time spreads

Modal group time spreads in an environment consisting of a stratified background on which a small-scale perturbation, due for example to internal waves, is superimposed have recently been investigated (Udovydchenkov and Brown, 2008). In this paper it is shown that there are three contributions to the time spread - the reciprocal bandwidth, a deterministic dispersive contribution, and a scattering-induced contribution. The dispersive and scattering contributions are controlled by β. This work provides a foundation for much of the LOAPEX experiment data analysis effort described below (see item 5).

2. Beam dynamics

The dynamics of directionally narrow acoustic beams have recently investigated by Beron-Vera and Brown (2009). Both the spatial and temporal spreads of narrow beams were shown to be controlled by α (or its mode equivalent β). This conclusion is supported by both ray- and mode-based analyses.

3. Resonant scattering and resonance widths

A correct, but not widely utilized, description of the mechanism underlying sound scattering in a waveguide (e.g., mode coupling) is resonant scattering. Resonances are excited between the background rays, which are periodic in range, and periodic structures in the sound speed perturbation. For a narrowband (in horizontal wavenumber) perturbation only a small number of resonances are excited, while for a broadband perturbation many resonances are excited. As a first step towards better understanding and quantifying this process, a general expression for resonance widths has been derived (Rypina et al., 2007). Resonant scattering is being explored with a focus on ocean variability caused by internal tides. Our focus on internal tides is based on the expectation that this will be one of the dominant forms of ocean variability during the 2009/2010 Philippine Sea experiment. This work is being done in collaboration with I. Rypina and I. Udovydchenkov at WHOI.

4. LOAPEX analysis

The PI's work (in collaboration with I Udovydchenkov at WHOI and the experimental groups at APL/UW and SIO) on the analysis of LOAPEX measurements is near completion. This effort is closely linked to the modal group time spread work described in item 1, above. Drafts of two papers have been written. The first paper focuses on near-axial modes, corresponding to small mode numbers. Those modes are the simplest to deal with from a measurement perspective, but from the perspective of scattering theory, those modes present special challenges. The second paper focuses on higher order modes. From the perspective of the scattering theory that has been developed, those modes present no special challenges, but, because the LOAPEX experiment was not designed to measure those modes, they present special signal processing difficulties. In both papers, in spite of the particular challenges present, agreement between data-based estimates of modal group time spreads and theoretical predictions is good.

5. *Mode filtering and energy conservation*

In the course of the PI's work (with I Udovydchenkov) on mode processing of LOAPEX measurements, it was discovered that most commonly used mode filters, including filters that are presented as being optimal in some sense, do not conserve energy. (The energy conservation constraint follows from the orthogonality of the acoustic normal modes.) This led to an unanticipated brief theoretical detour whose focus is the importance of constraining mode filters to conserve energy. A short paper on this topic is being prepared.

RESULTS

Although our goal of developing a theory of acoustic fluctuations in long-range propagation is not yet complete, significant progress has been made. The forward scattering physics are much better understood than was the case a few years ago. An important result of the PI's work over the past few years is conceptual: the forward scattering of sound — by internal-wave-induced perturbations, for example — is largely controlled the background sound speed structure. Thus, sound scattering in environments with identical internal-wave-induced sound speed perturbations but different background speed structures may be very different. This statement is supported by observations, simulations and theoretical analysis – both ray- and mode-based.

IMPACT/APPLICATION

Our work is contributing to an improved understanding of the basic physics of low-frequency long-range sound propagation in the ocean, and the associated loss of signal stability and coherence imposed by environmental variability. This knowledge contributes to an understanding of the limitations of advanced signal processing techniques, such as matched field processing.

TRANSITIONS

Our results are being used to interpret (reinterpret, in some cases) data collected in long-range propagation experiments, e.g. SLICE89, AET, SPICE04 and LOAPEX. We are unaware of transitions to system applications.

RELATED PROJECTS

The PI and collaborators listed above actively collaborate with the NPAL (North Pacific Acoustic Laboratory) groups at SIO (P. Worcester, W. Munk, B. Cornuelle, M. Dzieciuch), APL/UW (J.

Mercer, B. Dushaw, R. Andrew, F. Henyey and M. Wolfson) , UHawaii (B. Howe) and NPS (J. Colosi).

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PUBLICATIONS

Udovydchenkov, I. A., and M. G. Brown, 2008, Modal group time spreads in weakly range-dependent deep ocean environments, *J. Acoust. Soc. Am*. **123**, 41-50. [published, referred]

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